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Dielectric Properties of Tantalum Oxynitride Films

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Recently tantalum nitride (TaN) has attracted considerable interest for thin film capacitors. TaN capacitors are preferred to β-tantalum capacitors for hybrid integrated circuits as they have low dielectric losses ($\tan\delta$), a low temperature coefficient of the capacitance (TCC), and they are more stable /1 to 3/. However, the optimum fabrication conditions of TaN capacitors are still under investigation. The present report contains some studies on TaN capacitors using aluminium as counterelectrode instead of conventional NiCr-Au alloy /4/. The results are explained with existing theories.

TaN films (0.3 μm) are deposited on chemically and ultrasonically cleaned glass and alumina substrates at a rate of 0.012 μm/min. Films are deposited by reactive sputtering in a mixed atmosphere of ultra-high pure argon and nitrogen. TaN films of different N_2 concentration are obtained by varying the nitrogen pressure from 0.2 to 1% of the argon pressure which is maintained at 10^{-2} Torr during sputtering. Sputtered films are baked at 200 $^{\circ}$C for 3 h. Capacitor patterns are defined by using the standard photolithographic process and the films are anodized to 150 V in 0.01% citric acid solution at a current density of 1 mA/cm^2. To complete the fabrication of the capacitor aluminium (99.99%) is deposited (0.08 to 0.1 μm thick) as counterelectrode by vacuum evaporation at 2×10^{-5} Torr.

For samples containing different nitrogen concentration the leakage current, TCC, $\tan\delta$, and the capacitance at 1 kHz are measured before and after heat treatment. The results are presented in Fig. 1 and 2.

Capacitors ($\approx$ 1000 pF) are subjected to leakage current (I_L) tests. For samples containing 0.2 to 0.8% nitrogen the leakage current at 15% of the formation voltage is found to be less than 2×10^{-9} A. For undoped samples I_L is about five times higher. This is expected because in case of doped films the presence of nitrogen compensates the defective states which are responsible

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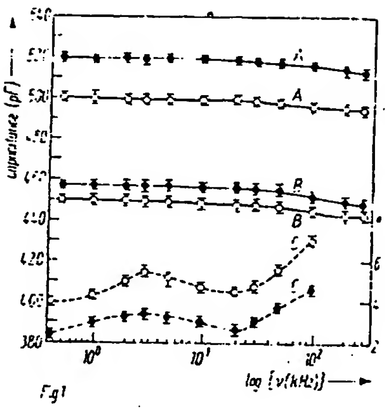

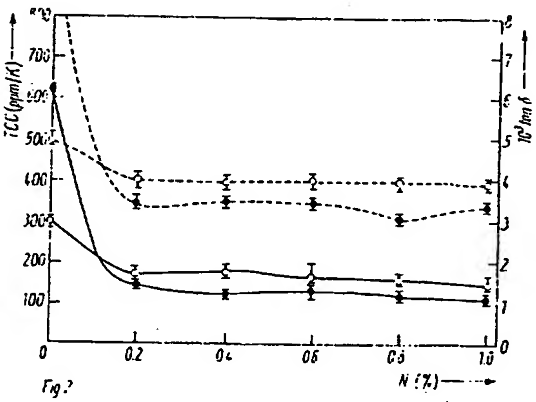

Fig. 1. Dependence of capacitance (——) and tan δ (---) on frequency. (A) Undoped samples, (B), (C) 0.6% nitrogen doped samples; ♁ before heat treatment, ♁ after heat treatment

Fig. 2. Variation in TCC (——) and tan δ (---) as a function of the nitrogen doping level (% of argon pressure); ♁ before heat treatment, ♁ after heat treatment

for dc conduction in the oxide. These values of I_L are slightly higher than those reported by earlier authors using NiCr-Au as counterlectrode /3/.

The variation in capacitance with frequency is shown in Fig. 1. About 1% fall in capacitance is noticed when the frequency increases from 10 to 100 kHz. The decrease in capacitance with increase in frequency is common for all capacitors of this type. To some extent, the frequency at which the capacitance falls, depends on the porosity of the oxide film and the processing factors. After heat treatment at 300 °C for 2 h, the frequency dependence of the capacitance remains almost the same. However, for samples containing 0.6% nitrogen the capacitance increases by 1.5%, whereas it rises by about 4% in case of undoped samples.

The dependence of the dielectric loss (tan δ) on frequency is also shown in Fig. 1 for 0.6% nitrogen doped samples. The dielectric loss increases with frequency in the range 500 Hz to 3 kHz. However, it falls when the frequency increases from 3 to 20 kHz. This might be attributed to a decrease in the

electronic polarizability /5/. According to Westwood et al., the fall in tan δ seems to be a characteristic property of the aluminium counterelectrode /4/. Beyond 20 kHz, the series resistance becomes more predominant and this leads to a rise in tan δ with increase in frequency. After heat treatment tan δ falls by about 35%.

The dependence of TCC (between -80 ^{o}C and +100 ^{o}C) and tan δ on nitrogen concentration is shown in Fig. 2. Our results show that typical values of TCC and tan δ are 300 ppm/K and 0.005, respectively, for capacitors made from β-tantalum. For nitrogen doped samples it is observed that both TCC and tan δ decrease. For example, in case of capacitors with 0.2% N_2 content, TCC is found to be 175 ppm/K and tan δ is 0.004. Further increase in the N_2 content shows a negligible influence on these parameters. When these capacitors are subjected to heat treatment at 300 ^{o}C for 2 h, for capacitors formed from undoped films TCC and tan δ increase from 300 to 625 ppm/K and from 0.005 to 0.012, respectively, whereas for nitrogen doped samples TCC and tan δ fall by 50 ppm/K and 0.001, respectively.

Now the results will be explained in the light of the existing theories and experimental results. In case of capacitors made from β-tantalum films the increase in TCC and tan δ may be attributed to a conductivity gradient formed in the Ta_2O_5 layer due to heat treatment. According to Smyth et al. /6/ oxygen, extracted from the oxide layer diffuses through the Ta_2O_5-Ta interface into the tantalum film. As a result, vacancies are formed in the oxide layer. Therefore, the conductivity of the oxide is very high at the tantalum-oxide interface compared to the conductivity at the oxide-counterelectrode interface. Due to this conductivity gradient the effective thickness of the dielectric decreases with a corresponding increase in TCC. At the same time, the series resistance increases resulting in higher tan δ. In case of N_2-doped Ta_2O_5 films, studied here, during heat treatment oxygen cannot be easily extracted from the oxide layer as most of the interstitial sites in the tantalum lattice are already filled by nitrogen and the dielectric is comparatively homogeneous. Thus, in $Ta_2O_5N_x$ films, no increase in TCC and tan δ should be noticed except for a slight increase in capacitance. However, the small decrease in TCC and tan δ shown in Fig. 2 may be due to a removal of the ions of citric acid and H_2O from the oxide layer during heat treatment. This explains the results shown in Fig. 1 and 2.

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In conclusion, it appears that the dielectric properties of tantalum oxynitride films are superior to those of tantalum oxide films. After heat treatment capacitors made with tantalum oxynitride as dielectric exhibit the most favourable values of tanδ and TCC namely, 0.003 and 120 ppm/K, respectively, at nitrogen doping corresponding to 0.8% of the argon pressure. Also, for these capacitors the dc leakage current is less than 2×10^{-9} A and the breakdown voltage lies between 75 and 80% of the formation voltage. These values are obtained by using aluminium as counterelectrode and they may find applications in hybrid integrated circuits.

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